BLIND BEAMFORMING FOR DS-CDMA SYSTEMS

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ABSTRACT

Code Division Multiple Access (CDMA) has been proposed as an efficient access method for cellular and personal communication systems outperforming the classical FDMA and TDMA techniques. But, in contrast to them, CDMA systems are interference limited, being the interferences mainly the other users.

A variety of methods have been proposed to combat this multi-access interference (MAI), such as the correlation detector, the maximum likelihood detector, linear detectors, subtractive interference cancellation detectors.

However, spatial diversity can be combined with the existing methods to further increase the reduction of the interference. Many efforts have been spent in this direction during the last years.

In this paper, a novel blind beamforming algorithm based on the introduction of an explicit redundancy structure within the spreading codes is described.

1. INTRODUCTION

Code Division Multiple Access (CDMA) has been proposed as an efficient access method for cellular and personal communication systems, e.g. IS-95 [1] and IS-665 [2]. It has been shown to offer higher capacity than the existing FDMA or TDMA methods but, in contrast to them, CDMA systems are interference limited.

Many different approaches have been devised to combat the *multi-access interference* (MAI), which is originated by the rest of the users [3]. The MAI problem can be further intensified by the *near-far effect*, which is due to the different geographical situation (distance to the base station and multipath propagation) of the mobile users.

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The conventional detector is nothing more than a bank of matched filters (also known as correlation detector). It assumes the MAI as *additive white Gaussian noise* (AWGN) and, in contrast to the so-called *multiuser detectors*, it does not use the information of all the users jointly (decentralized detector).

The optimum multiuser detector, *maximum likelihood detector*, was proposed in [4]; but even for a small number of users, its computational cost is unacceptable. Thus, suboptimum but still multiuser-based methods (centralized methods) have been proposed. One family of these suboptimum algorithms includes the so-called *linear detectors* (they perform a linear combination of the output of the matched filters to decouple the user's signals), such as the *decorrelating detector* [5, 6], the *minimum mean-square error (MMSE) detector* [7] and the *polynomial expansion (PE) detector* [8]. Another important family includes the *subtractive interference cancellation detectors*, which include the serial and parallel versions: *successive interference cancelation (SIC)* and *parallel interference cancellation (PIC)* [9]. They basically subtract a previous estimation of the user signals on an iterative basis, so that for each new estimation, each user will see less MAI.

In principle, all of the aforementioned methods were devised to combat the MAI based on a monosensor detection. Nevertheless, an approach to further increase the system capacity is the use of spatial processing with base station antenna arrays, also called *spatial diversity multiple access (SDMA)*. By using spatial diversity at cell sites, it is possible to use adaptive receive and transmit beamformers for each user, by which the interference signals (other users) are nulled. In this way, after the beamforming stage, the previously named detectors will see a nearly interference-free environment thanks to reducing the amount of co-channel interference from within the own cell and neighboring cells.

Many efforts have been spent in this direction of multisensor detection approach during the last years.The most straightforward method would be a temporal reference based beamforming algorithm [10], but it implies a loss of the efficiency of the system because of the reference signal. Nevertheless, the *pseudo-noise* (PN) sequence can be used as an implicit temporal reference. Another possibility is to use a blind beamforming approach by using the detected sequence as a self-reference (decision directed beamforming) [11], but this method may not converge in adverse conditions (high near-far effect).

More sophisticated methods have been devised, such as [12], in which a *phased array* is used after the MAI has been removed by means of a decorrelating detector; or the DEDYSS (DEcoupling of DYads of Spatial Signature) algorithm [13], which estimates the steering vector of each user so that it can be used in any of the classical spatial reference beamforming algorithms [10] (phased array, phased array with linear constraints, minimum variance, maximum SINR).

Nevertheless, all the previously mentioned methods for spatial, temporal and code combining need the detector to be synchronized with the user spreading code, which is not a very restrictive assumption for short PN sequences. But the synchronization with long PN sequences (where there are many hypotheses to test [14]) can be quite difficult if not impossible in presence of MAI with a strong near-far effect.

In this paper, a novel blind beamforming algorithm suitable for CDMA systems (specially interesting for long PN sequences) by means of fixed redundancy structures in the PN sequences is described. It does not need the global PN synchronization but a frame-PN one, which is much easier to achieve because it has far less hypotheses to test. Once the beamforming has been done, the global synchronization can be completed and the temporal and code methods previously named can work in a reduced MAI situation.

It is important to note that the redundancy is included in the PN sequence and not in the bit sequence, which means that the spectral efficiency of the system is maintained.

2. SIGNAL MODEL

Assuming narrowband and point-source plane-wave signals, the snapshot corresponding to NS impinging signals received at an antenna array of Q elements $\mathbf{x}(t) = [x_1(t), x_2(t), \ldots, x_Q(t)]^T$ is defined as:

$$\mathbf{x}(t) = \sum_{n=1}^{NS} \mathbf{a}(\theta_n)\sqrt{p_n}s_n(t) + \mathbf{n}(t) = \mathbf{A}\mathbf{s}(t) + \mathbf{n}(t) \quad (1)$$

where $\mathbf{a}(\theta_n)$ are the steering vectors of the signals (space signatures), $s_n(t)$ are the direct sequence modulated signals with power p_n and $\mathbf{n}(t)$ is the noise (AWGN) vector.

The received signal is, after beamforming with the beamvector $\mathbf{w}$:

$$y(t) = \mathbf{w}^H\mathbf{x}(t) \quad (2)$$

Performing the beamforming on a block basis and uniform snapshot sampling, it can be expressed as:

$$\mathbf{y}_q^T = \mathbf{w}^H\mathbf{X}_q \quad (3)$$

where $\mathbf{X}_q = \left[\begin{array}{cccc} \mathbf{x}_{q\cdot M} & \mathbf{x}_{q\cdot M+1} & \cdots & \mathbf{x}_{q\cdot M+(M-1)} \end{array}\right]$, M is the length of the block and q represents the block.

3. ALGORITHM DESCRIPTION

Users' signature in CDMA systems must present good auto and cross-correlation properties (to be able to separate the users one from another). There are a few families of such sequences that present these desired properties, e.g., Gold codes, large and small set of Kasami sequences [15].

The data stream of each user is modulated by its spreading signature, which means that an inherent temporal redundancy specific for each user has been introduced. It is possible, therefore, to use a blind beamforming algorithm based on this temporal diversity (code structure of the signal) different for each user. Nevertheless, this requires of PN synchronization, which represents an important drawback for long PN sequences.

The algorithm presented herein is based on an explicit fixed redundancy structure introduced within the PN sequence. In this new approach, segments of the original PN sequences are first generated to create then the redundant PN (RPN) segments. The receiver (base station) will use the knowledge of the redundancy structure to perform an exact prediction of the signal received and will be able to define an error which will be the key in the beamforming procedure. The redundancy can be seen as a self-reference system that yields an exact self-prediction. The idea of introducing a redundancy to be used for an error definition has already been used in other fields such as channel equalization [16], beamforming in frequency diversity schemes [17, 18] and error correction using linear codes [19].

The procedure consists on introducing the redundancy on a block basis using the fixed redundancy matrix $\mathbf{G}$ (different for each user):

$$\mathbf{rpn}_q = \mathbf{G}^T\mathbf{pn}_q \quad (4)$$

where the original $N \times 1$ PN frame, $\mathbf{pn}_q$, is transformed into the $M \times 1$ redundant PN frame, $\mathbf{rpn}_q$, being $R = M - N > 0$ the number of redundant chips. The redundancy structure considered is simply the repetition of certain chips with a possible change of sign (as can be seen in Figure **??**). The redundancy matrix has to be properly designed so that the desired properties of the original PN sequences are not destroyed. A redundancy factor can be defined as $F_R = \frac{R}{N+R}$.

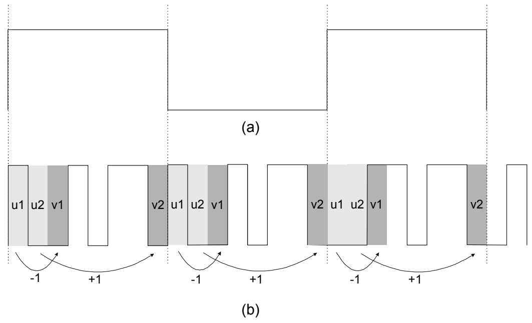

Figure 1: Scheme of the fixed structure of the RPN: (a) original BPSK bit sequence, and (b) spread signal of the DS-CDMA system (using a RPN).

The receiver will make use of an $M \times R$ parity check matrix, $\mathbf{H}$:

$$\boldsymbol{\varepsilon}_q = \mathbf{H}^T \mathbf{y}_q = \left(\mathbf{H}_u^T - \mathbf{H}_v^T\right) \mathbf{y}_q = \mathbf{u}_q - \mathbf{v}_q \tag{5}$$

where $\mathbf{y}_q$ contains the desired modulated RPN signal plus noise and interferences. The matrices $\mathbf{H}_u$ and $\mathbf{H}_v$, according to (5), can be seen as matrices that extract two different sets of diversity elements from a redundant vector, which can be used to perform the self-prediction:

$$\begin{aligned} \mathbf{u} &= \mathbf{H}_u^T \mathbf{y} && (6) \\ \mathbf{v} &= \mathbf{H}_v^T \mathbf{y} && (7) \end{aligned}$$

In general, the PN-frame period can be different to the symbol period, as long as it is a divisor of it, so that the self-prediction property is not destroyed. Note that in this procedure, not global PN synchronization but just a PN-frame one is needed.

The beamforming algorithm is based on the minimization of the *mean squared error* (MSE) using a second-order constraint to avoid the trivial solution:

$$\begin{array}{l} \min E\left\{\left\|\varepsilon_q^2\right\|\right\} \\ \text{subject to } \operatorname{Re}\left\{E\left\{\mathbf{u}_q^T \mathbf{v}_q^*\right\}\right\} = \phi_c > 0 \end{array} \tag{8}$$

which can be expressed as

$$\begin{array}{l} \mathbf{w}^H \mathbf{R}_{in} \mathbf{w}\big|_{\min} \\ \text{with } \mathbf{w}^H \mathbf{R}_d \mathbf{w} = \phi_c \end{array} \tag{9}$$

The cross-correlation constraint of (8) is very effective, because the desired signal is completely correlated in both branches of the diversity, whereas neither the noise nor the interferences are (for this to be true, the $\mathbf{G}$'s of all the users must be properly designed so that they do present a zero cross-correlation with respect to any other user structure).

The optimal solution to the quadratic constrained minimization of (8) is given by the generalized eigenvector $\mathbf{w}$:

$$\mathbf{R}_d \mathbf{w} = \lambda_{\max} \mathbf{R}_{in} \mathbf{w} \tag{10}$$

where (assuming the first source the desired one without loss of generality)

$$\begin{aligned} \mathbf{R}_d &= E\left\{\mathbf{X}_q \mathbf{H}_u \mathbf{H}_v^H \mathbf{X}_q^H\right\} + E\left\{\mathbf{X}_q \mathbf{H}_v \mathbf{H}_u^H \mathbf{X}_q^H\right\} \\ &= p_d \mathbf{a}(\theta_d) \mathbf{a}(\theta_d)^H && (11) \\ \mathbf{R}_{in} &= E\left\{\mathbf{X}_q \mathbf{H} \mathbf{H}^H \mathbf{X}_q^H\right\} \\ &= \sum_{i=2}^{NS} p_i \mathbf{a}(\theta_i) \mathbf{a}(\theta_i)^H + \sigma_n^2 \mathbf{I} && (12) \end{aligned}$$

The solution of (10) maximizes the *signal to interference plus noise ratio* (SINR):

$$\text{SINR} = \frac{\mathbf{w}^H \mathbf{R}_d \mathbf{w}}{\mathbf{w}^H \mathbf{R}_{in} \mathbf{w}} \tag{13}$$

yielding $\text{SINR}_{\max} = \lambda_{\max}$.

The design of different orthogonal redundancy structures (for different asynchronous users) is under the scope of this article but has been omitted for the sake of simplicity.

The proposed blind algorithm is based on a structural reference, this implies that it is a completely robust algorithm. It can perfectly handle antenna elements calibration errors and multipath environments, either frequency selective or non-frequency selective channels (for the last case, depending on the design of the redundancy structure $\mathbf{G}$, different optimality criteria can be used [20]).

The computationally expensive calculation of the generalized eigenvector can be easily implemented with a gradient-type adaptive algorithm minimizing the Lagrangian of the constrained minimization problem with respect to $\mathbf{w}^*$ [21]:

$$\frac{\partial \mathcal{L}}{\partial \mathbf{w}^*} = \mathbf{R}_d \mathbf{w} - \lambda \mathbf{R}_{in} \mathbf{w} \tag{14}$$

yielding the following adaptation rule:

$$\mathbf{w}(\mathbf{n}+\mathbf{1}) = \mathbf{w}(\mathbf{n}) - \boldsymbol{\mu}\left(\mathbf{R}_d - \lambda_n \mathbf{R}_{in}\right) \mathbf{w} \tag{15}$$

where μ is the step size parameter that controls both convergence and stability of the algorithm. Another adaptive powerful method is the *Power Iteration Method* [22], which allows the calculation of the eigenvector corresponding to the eigenvalue with greatest magnitude:

$$\mathbf{R}_{in}^{-1}\mathbf{R}_d\mathbf{w} = \boldsymbol{\lambda}_{\max}\mathbf{w} \qquad (16)$$

where the inverse matrix $\mathbf{R}_{in}^{-1}$ can be efficiently computed on an adaptive fashion using the matrix inversion lemma.

4. SIMULATIONS

The simulations were performed with a *uniform linear array* (ULA) of 7 antenna elements, using a separation of half wavelength. The scenario was composed of a desired BPSK signal (SNR=0dB) impinging from an angle of 30^o and 4 interfering BPSK signals impinging from the angles -30^o, 0^o, 50^o and 80^o (INR's of 40, 20, 30 and 20dB) respectively. All the present signals (corresponding to different users) were spread using Gold sequences (long PN sequences of 1023 chips) with a spreading factor (also known as processing gain) of SF = 31 chips per symbol, creating a DS-CDMA scenario with 5 users.

The parameters of the redundancy structure are: N=29 and R=2 (M=31), which means that only 2 chips out of 31 per symbol are used in the beamforming procedure.

The power iteration method was used for the beamforming, yielding the SINR evolution depicted in Figure 2. The estimated beamformer corresponding to the steady state and the theoretical optimum one (in the sense of maximum SINR) can be seen in Figure 3, yielding a SINR of 7.18dB (being the SINR without the use of arrays of -40.49dB and the maximum attainable with the use of the optimum theoretical beamformer of 7.80dB). It is important to note that the given output SINR's were computed before the despreading stage, which, theoretically, would give an increase of $10\log_{10}\mathrm{SF} \simeq 15$dB.

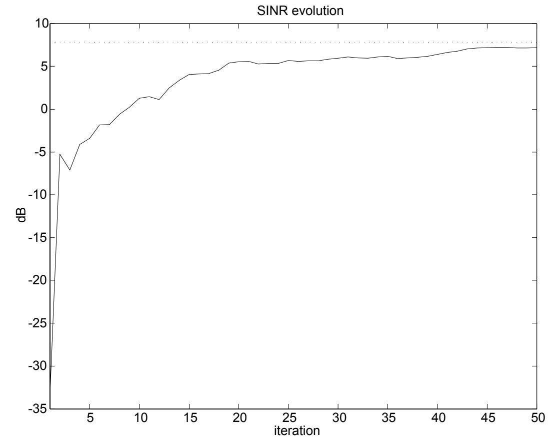

Figure 2: SINR evolution of an array of 7 antenna elements using the power iteration method for an scenario with a desired BPSK signal with a DOA of 30^o (SNR=0dB) and 4 orthogonal unsynchronized BPSK interfering signals impinging from angles of -30^o, 0^o, 50^o and 80^o (INR's of 40, 20, 30 and 20dB) respectively; where the parameters of the redundancy structure are N=29, R=2 and each iteration corresponds to one frame. Solid line: corresponding to the estimated beamformer. Dotted line: corresponding to the optimum value achievable.

5. CONCLUSIONS AND FURTHER WORK

A novel adaptive blind beamforming algorithm, based on an explicit redundancy structure introduced into the spreading codes of the users, has been presented. The method is particularly intended for DS-CDMA systems in which different users share the same time-frequency support using quasi-orthogonal codes. Spatial processing allows interference cancellation based on their directions of arrival. Simulation results have shown the effectivity of the proposed scheme as long as the interferences have different DOA's from the desired signal. Since the method is based on a structural reference, it is robust to any kind of antenna elements calibration errors and to multipath environment.

A very important issue out of the scope of this paper is the acquisition of frame synchronization, which is currently under investigation.

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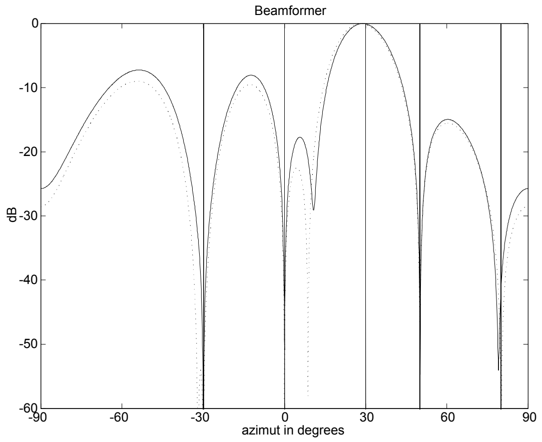

Figure 3: Steady-state beamformer of an array of 7 antenna elements using the power iteration method for an scenario with a desired BPSK signal with a DOA of 30^o (SNR=0dB) and 4 orthogonal unsynchronized BPSK interfering signals impinging from angles of -30^o, 0^o, 50^o and 80^o (INR's of 40, 20, 30 and 20dB) respectively; where the parameters of the redundancy structure are N=29, R=2. Solid line: estimated beamformer using the power iteration method (SINR=7.18dB). Dotted line: optimum theoretical beamformer (SINR=7.80dB).

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